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SAND2004-3981
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Conversion of the West Hackberry Geological Site Characterization Report to a Three-Dimensional Model

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Abstract

The West Hackberry salt dome, in southwestern Louisiana, is one of four underground oil-storage facilities managed by the U. S. Department of Energy Strategic Petroleum Reserve (SPR) Program. Sandia National Laboratories, as the geotechnical advisor to the SPR, conducts site-characterization investigations and other longer-term geotechnical and engineering studies in support of the program. This report describes the conversion of two-dimensional geologic interpretations of the West Hackberry site into three-dimensional geologic models. The new models include the geometry of the salt dome, the surrounding sedimentary layers, mapped faults, and a portion of the oil storage caverns at the site. This work provides a realistic and internally consistent geologic model of the West Hackberry site that can be used in support of future work.

ACKNOWLEDGEMENTS

` This work was supported by the U.S. Department of Energy, Strategic Petroleum Reserve Project Management Office, in New Orleans, Louisiana.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

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INTRODUCTION

The West Hackberry salt dome, located in southwestern Louisiana (Figure 1), is one of four underground oil-storage facilities run by the U. S. Department of Energy (DOE) Strategic Petroleum Reserve (SPR) Program. Sandia National Laboratories (SNL), as the geotechnical advisor to the DOE SPR Project Office, conducts site-characterization investigations and other longer-term geotechnical and engineering studies in support of the program. This report describes the conversion of two-dimensional (2-D) geologic interpretations to three-dimensional (3-D) geologic models of the West Hackberry SPR site. This work provides a more realistic and consistent geologic model of the West Hackberry site that can be used in support of future work.

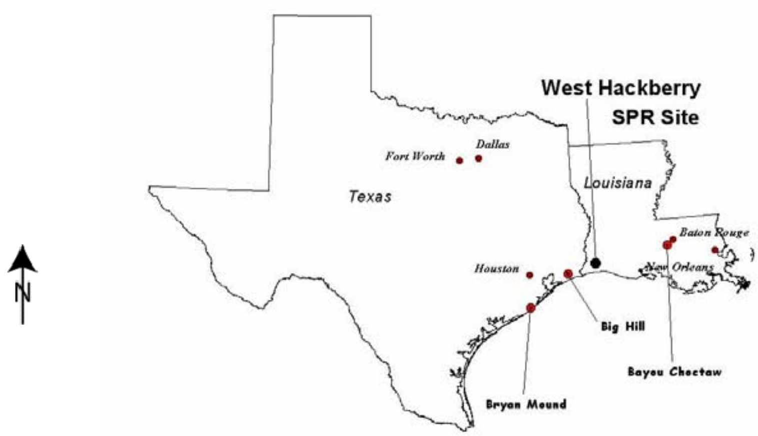

Figure 1. Index map showing the location of the West Hackberry SPR facility and other SPR sites**.**

CONVERSION OF EXISTING REPORTS TO 3-D

Current knowledge of the subsurface geometry and extent of the West Hackberry salt dome and its surrounding sedimentary environment is based largely on geologic interpretations of borehole records and logs, some of which were drilled and recorded in the early twentieth century. These data have been compiled, interpreted and published in two site characterization reports that include structural contour maps, geologic cross-sections, and data tables (Whiting, 1980; Magorian et al., 1991). The interpretations contained in these reports use 2-D models to represent the 3-D structures at the site. This was standard practice at the time that these reports were written. Today modern geological modeling software is available that allows full 3-D representations of geologic features to be constructed and visualized. These modern tools have significant advantages over the older 2-D methods of geologic characterization. Many errors and geometric inconsistencies are obscured by 2-D representations of 3-D structures. Strict rules inherent in a true 3-D model will not allow for these inconsistencies. For example, a geologic feature, such as a fault, that is represented in several 2-D “slices” of a geologic model may look geologically reasonable in each slice but when these slices are combined in true 3-D space, the configuration of the fault no longer seems geologically plausible. In such cases the 3-D model allows the geologist to visualize the structure and judge its validity. Moreover, features in 3-D models have easily measurable surface areas and volumes allowing the models to be used for quantitative engineering work.

In an effort to maximize the value of the existing geologic site-characterization data at West Hackberry without performing a full re-characterization of the site, SNL has converted the 2-D models that are included in the two site characterization reports (Whiting, 1980; Magorian et al., 1991) to a true 3-D site model. This site model includes the geometry of the salt dome, caprock, selected caverns used for oil storage, and lithologic base or tops of mapped sedimentary units and faults that surround the dome. This report presents the methodology and resulting 3-D models of the geologic and engineered structures within and immediately surrounding the West Hackberry salt dome.

The 3-D modeling environment used for this work is the Mining Visualization System (MVS), from C Tech Development Corporation (www.ctech.com). This application includes geostatistical algorithms that allow the user to convert a collection of raw data points into a coherent 3-D model. In addition, MVS allows the user advanced visualization and analysis techniques in order to extract useful information from the models.

EXISTING DATA

Site Characterization Reports

The original geologic characterization of the West Hackberry site was completed in 1980 and documented in a Sandia National Laboratories SAND Report (Whiting, 1980). When the report was compiled there were five Phase 1 caverns, which produced brine as chemical feed stock prior to the establishment of the SPR program. The report was written to help DOE decide where to develop the 17 additional Phase 2 oil-storage caverns that presently exist within the dome. There were three main objectives of the original site characterization report: (1) Review cavern stability, integrity, and usability for both existing and planned caverns, (2) produce a comprehensive geological site characterization study from existing data, and (3) summarize work that had been done to characterize the physical and chemical properties of the domal salt at West Hackberry.

The second objective, which is the focus of the present model conversion activity, was met by compiling historical drilling records, plotting borehole locations on 2-D maps, contouring depths to the base or tops of key geologic units, and drawing geologic cross-sections across the site. Borehole locations and depths to the base or top surface of certain geologic units were included as data tables in the report. The report only included information related to the configuration of the salt, caprock, and a unit referred to as the “B” Sand, which is located between the top of caprock and the ground surface.

A site characterization update report was completed after the 17 Phase 2 oil-storage caverns were leached (Magorian et al., 1991). The report includes information from both commercial wells drilled after the original report was completed and 18 wells drilled in preparation for solution mining of the Phase 2 caverns. The objectives of the update report were as follows:

1. Improve the models of the salt dome and surrounding sedimentary units,
2. Characterize the subsidence history over West Hackberry SPR caverns, and
3. Assess potential flooding during future site operations.

This characterization update report included new structure contour maps of the top of salt and caprock as well as the top of two deep geologic units surrounding the dome (the Anahuac and Hackberry shale units). In addition, updated geologic cross-sections incorporating the new layers were included. The new geologic interpretations were based on information from the construction of the new caverns and access to logs from commercial wells surrounding the dome.

Well Information

Appendices in the original site characterization report contain well locations and depths to the tops of the salt and caprock and the base of the “B” Sand. The updated site characterization report appendices include all available well data in table format. These tables include depths to the tops of multiple geologic and biostratigraphic units including the Anahuac and Hackberry shale units. However, the data in these tables do not list well location coordinates but only identify wells by section number and sequence number. These data were presumably used to generate the structure contour maps contained in the update site characterization report. Unfortunately, the well numbers used in the original site characterization report do not appear to use the same sequence numbers for the same wells as the update report. Because the well locations could not be correlated it is not possible to use stratagraphic information in the update report to directly model the geology, rather we rely on the available interpretations of these data in the form of structural contour maps of the Anahuac and Hackberry shales.

Structure Contour Maps

Structure contour maps define the geometry of a geologic interface, such as the top or base of a geologic unit. The locations of fault intersections with that interface may also be represented by breaks and horizontal offsets of one or more contours. Structure contour maps were included in the original West Hackberry site characterization report (Whiting, 1980) for the top of salt, top of caprock, and base of “B” sand units. The updated characterization report (Magorian et al., 1991) includes updated structure contour maps for the top of salt and top of caprock units, along with structure contour maps for the tops of both the Anahuac and Hackberry shale units.

Geologic Cross Sections

Various geologic cross sections were included in the site characterization reports. These cross sections were constructed by projecting well data to cross-section lines and plotting the depths of geologic units with distance along the lines. The cross sections from the original characterization report portray the salt dome, caprock, and overlying “B” Sand. The cross sections from the updated characterization report do not display the “B” Sand, but do include the top surfaces of both the Anahuac and Hackberry shale units.

Cavern Sonar Surveys

The geometric configurations of the underground storage caverns leached into the salt mass are recorded at various stages during leaching and at episodic intervals during ongoing cavern operation through the use of downhole sonar-surveying equipment that is run inside the casing and any tubing in a cavern well. This equipment consists of a wireline tool, which contains a transmitter and a primary receiver, and a secondary receiver that allows determination of the velocity of the medium immediately surrounding the tool (either oil or brine). The electronics and physical design of the tool allow directional measurements using a tightly focused sonar beam and a directional receiver. Downhole rotational orientation of the tool is determined via magnetic orientation techniques.

2-D graphical representations of sonar caliper survey logs are included in the original site characterization report for caverns 6-9 and 11 at the West Hackberry SPR site. The updated site characterization report presents only stylized cavern profiles of nominal diameter and height for caverns 101-117. Digital sonar datasets are now available for 12 of the 22 oil-storage caverns at West Hackberry and 3-D models of these caverns are included in this model conversion report.

Geologic Units Identified at West Hackberry

Table 1 lists the geologic units in the vicinity of the West Hackberry SPR site that were included in the original site characterization report (Whiting, 1980). As is typical of this interval in the Gulf coast, the section is dominated by a complex sequence of sands and shales. The principal emphasis of site characterization has been to identify selected “tops” or “bases” of intervals, rather than on the full thickness of each geologic unit. Table 1 indicates which layers are included in this model-conversion report.

Table 1. Geologic names and unit surfaces in use at West Hackberry

Age Epoch	Stage	Formation	Symbol	Lithology	SPR model	Stratigraphic Unit	Biostratigraphic Zone
Pleistocene	Wisconsin						
		Prairie	a	sand and gravel			
		Montgomery	s	mud			
	Illinoian		I	sand and gravel			
		Bentley	(p)	mud			
	Kansan		ka/ks	sand and gravel			
		Williana		mud			
	Nebraskan		ne	sand and gravel			
Pliocene		Lafayette		gravel			
Miocene			PL	silt, mud, and sand			
			MI	mud and sand			
		Upper					
			A	sand and gravel			*Bigenerina floridana*
				mud			
			B	sand and gravel	X		
				mud			
			L	marine sand			*Textularia*
			2	deltaic sand			*Bigenerina nodosaria*
				mud			
			W	deltaic sand			*Textularia stapperi*
				mud			
		Middle					
			BH	unconformity			*Bigenerina humblei*
				shale			
			CI	thin sands			*Cristellaria*
			CO	sand			*Cibicides carstensi opima*
			AB	shale			*Amphistegina*
		Lower					
			RL	marine sand			*Robulus*
			OP	bituminous limestone			*Operculinoides*
			CA	sand and shale			*Cibicides*
			MA	sand			*Marginulina ascensionensis*
				shale			
			SD	thin sand			*Siphonina davisi*
Oligocene		Anahuac	DR	shale	X		*Discorbis*
			H	coral reef			*Heterostegina*
			MH	sand			*Marginulina howei*
				shale			
		Frio	F	sands			
			CH	marine sand			*Cibicides hazzardi*
			HB	geopressured shale	X	Hackberry	
		Vicksburg	VX	black shale			

Modified after table 1 of Magorian and others, 1991. "SPR Model" - presented as structure contour maps that have been converted to 3D models.

CONVERSION METHODOLOGY

In this section of the report we describe the methods used to convert the 2-D geologic interpretations included in the two site characterization reports into a 3-D geologic model of the West Hackberry SPR site. The complete 3-D model consists of a collection of components, each of which required a distinct conversion methodology. These methodologies are described below.

A Note on Coordinate Systems

Computerized geologic modeling mandates the use of a standardized coordinate system. In contrast, manual “spotting” of well locations and mapping on physical paper is much less demanding in this regard, as locations are typically placed relative to land-survey section lines or other well locations and construction of the model is by hand. Computer-based modeling and visualization are based on mathematical computations, with the result that all coordinates of represented features must be consistent.

The vast majority of oil and gas data for the Gulf Coast have been recorded in state plane coordinates, which for this part of the state of Louisiana is the south zone of that system. The Louisiana state plane coordinate system is a Lambert conformal conic projection, in practice almost invariably referenced to the North American Datum of 1927 (NAD-27). A few more recent 7.5-minute topographic maps published by the U.S. Geological Survey in this region use a state-plane system based on NAD-83, the North American Datum of 1983. However, virtually all historical geographic information uses the NAD-27 system.

The site characterization reports for the West Hackberry site do not state explicitly what coordinate system was used. However, the absolute magnitudes of the coordinates shown by marginal ticks on maps and figures correspond approximately to NAD-27. Because the magnitudes of roughly similar positions in other systems are markedly different (by design), we have assumed that the existing coordinates belong to the Louisiana state plane coordinate system, south zone, NAD-27.

Generation of Salt Dome Model

Both the original (Whiting, 1980) and updated (Magorian and others, 1991) site characterization reports present models of the West Hackberry salt dome as structure contour maps representing the top surface of the salt dome. These two representations of the salt geometry were converted to 3-D MVS models. The method used to generate the 3-D representation of the salt dome margin is documented in a separate report (Rautman and Stein, 2003).

The method involves digitizing the various structure contours on the top of salt in calibrated *x*- and *y*- state-plane-coordinate space. Each digitized point is then assigned the relevant elevation (depth) as the *z*-coordinate value; depth values are constant by definition for a given contour. The order of the digitized points constituting each contour line in the source document is maintained.

For the full set of digitized contours, corresponding 3-D points on successively deeper and shallower contour rings are connected using the external software code, **`ctr2evs`** (Rautman and Stein, 2003), to form a mesh comprised of quadralateral and triangular elements, similar to those used in finite-element models. This process is shown conceptually in Figure 2. The MVS geological modeling software uses such explicit finite-element type meshes, specifying the nodal coordinates and the connectivity among the nodes, as the basis for visualization of all contained features. Thus, the model implied by the flat, 2-D structure contour map is visualized directly by the software in three dimensions.

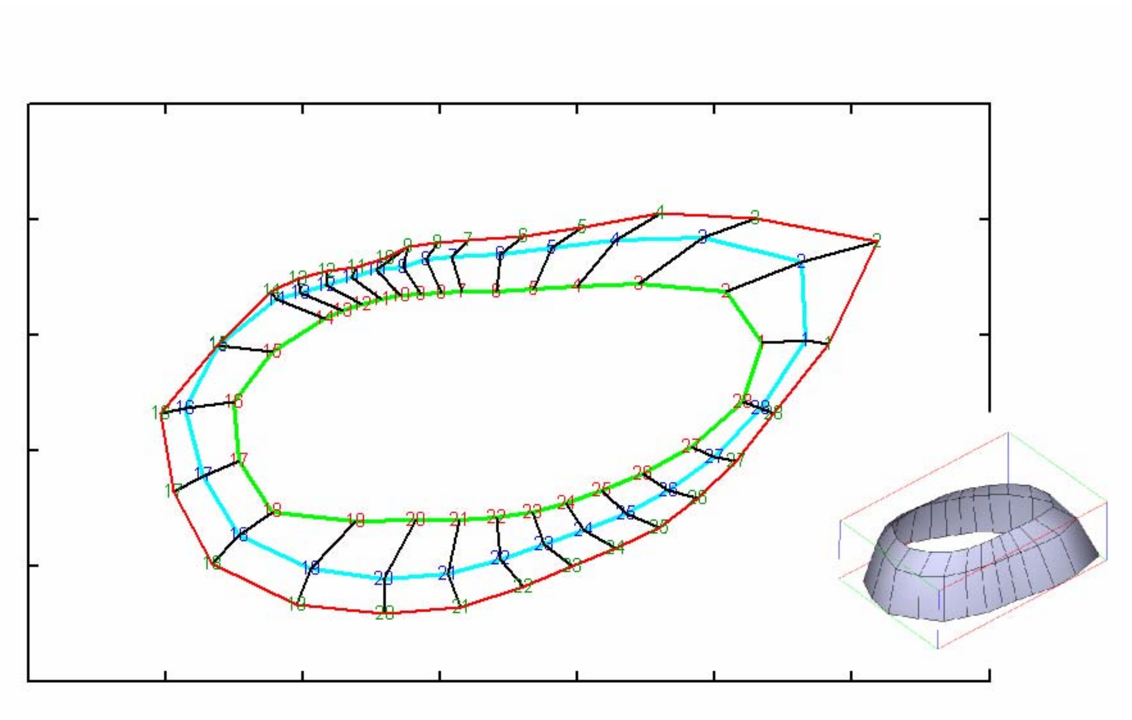

Figure 2. Conceptual representation of the process of constructing a finite-element-like mesh to represent the flanks of a salt dome from successive digitized structure contours on the top of salt. Equal numbers of points are defined on each successive contour and these points are connected between contours. Inset: resulting 3-D mesh object.

Because the crest of a salt dome is essentially flat lying, in marked contrast to the steeply plunging flanks of a dome, the structure-contour representation of the top-of-salt surface is generally somewhat simplistic unless supplemental contours are provided at a closer vertical spacing than that typically used to represent the flanks. The uppermost part of the salt dome has been modeled using the top-of-salt elevations from the available well control. This includes principally the various cavern wells, although a small number of other wells have also been included.

Modeling of these crestal top-of-salt picks was performed using a proprietary implementation of the geostatistical algorithm known as kriging. Kriging in general is merely a form of least-squares linear regression (Deutsch and Journel, 1998), in which the observed values (elevations of the top-of-salt picks) are interpolated at unsampled locations onto a quasi-regularly spaced finite-element-type mesh (Figure 3) as a weighted average of the known data within a local search neighborhood. The weights applied to the observations are computed via solution of a covariance matrix that considers both the distance from each measurement location to the point being estimated and a mathematical model — the variogram — derived from the data, describing statistical variation of the different measurements in space.

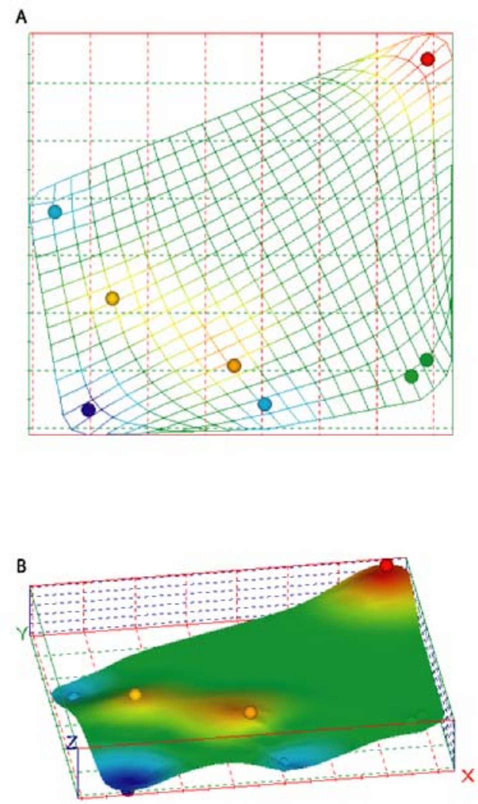

Figure 3. Conceptual representation of interpolation of scattered data points onto a finite-element-type mesh within MVS. (a) observed data and mesh (colored by value); (b) resulting surface. No scale.

Within the MVS software package, kriging of geological surfaces is implemented in the module **`Krig3D_Geology`**. This module uses a proprietary "expert system" approach to compute the variogram model of the data for each geologic horizon separately, and then sequentially kriges each horizon using the appropriate variogram model and the relevant observed data. The meshes representing the two portions of the dome were then merged using the MVS module **`merge_field`** to produce a combined surface for visualization.

Generation of Sediment Model

To convert the sediment models (the base of the "B" Sand and the tops of the Anahuac and Hackberry shale units) to 3-D models each mapped contour line was digitized at a spacing visually determined to capture the necessary details of the topology of the surface. The resulting *x-y* coordinate pairs were assigned the (constant) elevation value (*z* coordinate) appropriate to the contour in question and the *x-y-z* triples were provided to the MVS geologic modeling software module **`Krig3D_Geology`**, which successively kriges each individual geologic horizon. The structure contour map for the base of the "B" Sand includes numerous fault traces that partition the surface into distinct fault blocks. Since there are only subsets of contours in each fault block, digitized point depths from individual boreholes were also included in the dataset that was kriged for the final model. For the Anahuac and Hackberry shale models only the digitized contours were kriged.

Generation of the Caprock Model

The two versions of the caprock model overlying the West Hackberry salt dome were generated, in a similar manner to the sedimentary horizon models just described, using **`Krig3D_Geology`** applied to digitized contour data from the structure-contour and isopach maps contained in the original and updated site characterization reports (Whiting, 1980; Magorian et al., 1991). As with the sediment model, the relevant structure contour maps for the top-of-caprock and the top-of salt surfaces were digitized in calibrated *x-y state-plane* coordinate space and converted to MVS input files. For the isopach model, the thickness contours on the isopach maps were digitized and kriged.

Generation of Fault Models

Each site characterization report included selected fault traces on structure contour maps. In the original report (Whiting, 1980), fault traces were identified on only one structure contour map (base of “B” Sand). Without these faults being identified at other depths it is only possible to represent these features as projected lines on a 3-D surface. In the update report (Magorian et al., 1991) two faults that intersect both the Anahuac and Hackberry shale top surfaces were identified and thus allow the opportunity to convert these to true 3-D models of the fault planes. To model these faults we digitized the fault traces from each structure contour map and divided the traces into ten equally spaced (x,y) points. These two-dimensional points were then projected onto the modeled three-dimensional geologic surface (using MVS module: **`geologic_surfmap`**), resulting in ten (x,y,z) points, where z is the elevation of the fault trace *on the geologic surface*. The process was repeated for each geologic surface intersected by the fault. Finally the fault plane model was generated by connecting the (x,y,z) points from both surfaces intersected by the fault into a triangulated irregular network using the MVS module: **`scat_to_tin`**. This method produces a fault plane bounded by each sedimentary surface; the actual fault planes extend beyond the boundaries of these two surfaces.

Generation of the Cavern Models

A sonar survey was converted to a 3-D model by computing the coordinates of the reflecting surfaces from the downhole measurements using simple trigonometry. The raw output from a typical downhole sonar survey consists of a set of radial distance measurements plus the depth and orientation information necessary to locate the spatial positions from which those radial measurements were obtained. The positional data comprise the depth of the sonar tool for each 360-degree sweep of the cavern, the angular inclination of the beam direction (up, down, or horizontal), and the azimuth relative to north.

Because the depth, rotation, and inclination sequence are known, it is a relatively simple matter to connect the points where the focused sonar beam reflects from the cavern wall to form a two-dimensional surface in 3-D using quadrilateral elements. It should be noted that sonar surveys were available in digital format and processed into 3-D visualization models for only 12 of the 22 caverns at the site. Other cavern sonar surveys do exist in paper record format and could be converted into 3-D visualization models. However, this conversion from paper to digital formats is time consuming and should be undertaken as the need for these models arises.

It should be noted that modeling of the sonar surveys was conducted as though the sonar beam was essentially a line and that the reflecting surface was oriented normal to the direction of travel of the sonar pulse. Although this was a necessary and geologically reasonable assumption for many caverns and at most depths, it need not apply rigorously in all circumstances.

RESULTS

This section presents the resulting 3-D models of selected geological features that were converted from the original and the updated site characterization reports. As will become apparent, there are some fairly significant differences between the two versions of models — at least in detail. The major configurations of the salt dome in terms of the Strategic Petroleum Reserve, however, appear quite similar.

The 3-D geologic model of the West Hackberry SPR site is best illustrated using modern visualization tools that allow the viewer to “interact” with the model and examine it from different angles and at different levels of magnification. MVS has a free viewer (4-DIM [*4-D*imensional *I*nteractive *M*odel] viewer) that allows one to rotate and view the 3-D models from a variety of angles and at different magnifications. A set of .4D files is included on a CD that is part of this report. Appendix A describes how to install the viewer software and Appendix B lists the 4-DIM files and frames included on the CD.

A less ideal way to view these models is by examining still images. We include a set of these images in the sections that follow. Each still image has an associated 4-D file that is noted in the figure captions.

Salt Dome Model

The geometry of the West Hackberry salt dome model from the original site characterization report is shown using several perspective views in Figure 4. The views are from 30 degrees above the horizontal. A view from directly overhead is shown in Figure 5; this view approximates the original structure-contour map from which the model was generated.

The dome is roughly rectangular in shape, but with prominent rounded corners and a number of irregular crenulations along the flanks. The rectangular analogy is less so on the eastern part of the dome, where the contours indicate a narrowing to a broad, eastfacing point. The crest of the dome is relatively flat; note the change in the contour interval above 3000 ft subsea. However, the center of the dome crest appears lower than the margins of the crest, and there is some degree of irregularity to the upper surface of the dome.

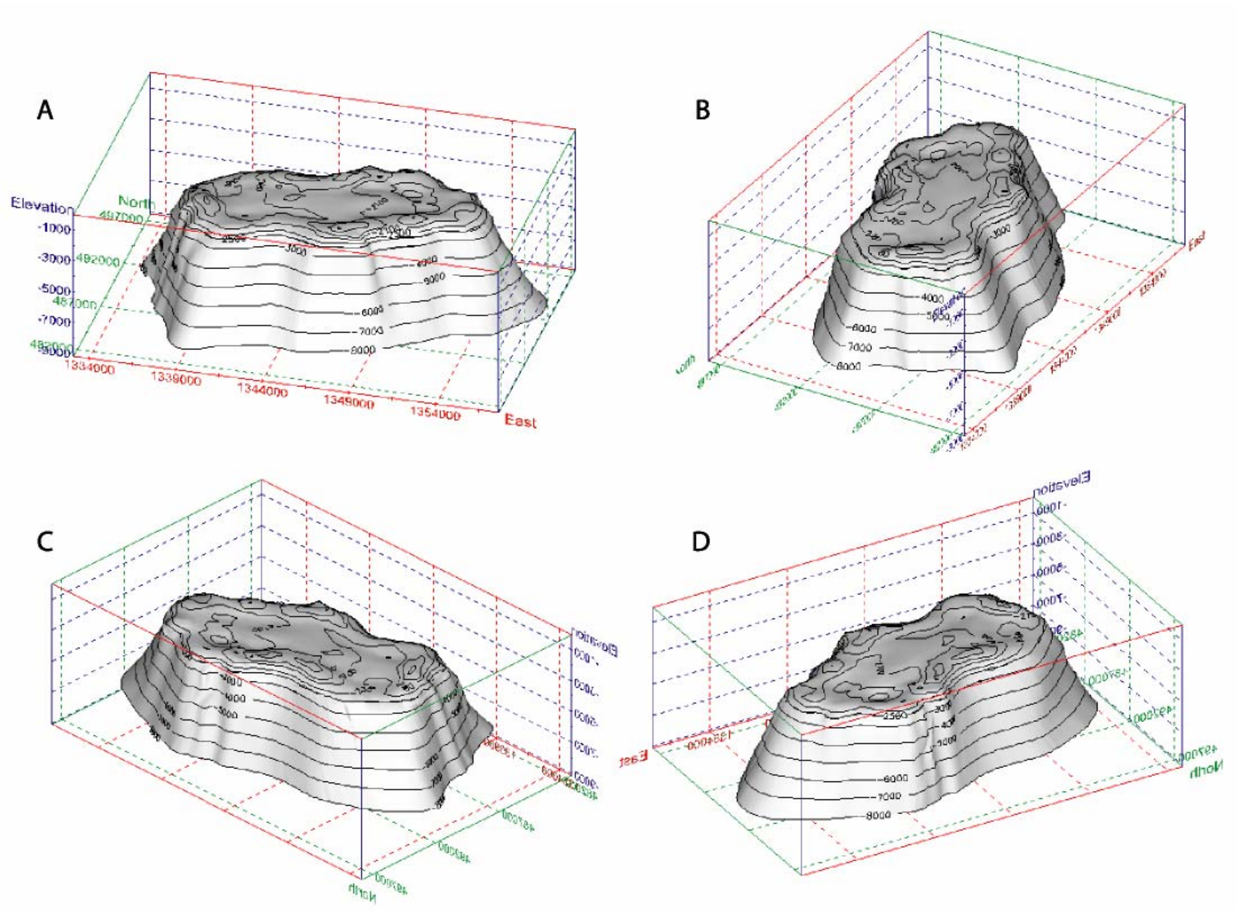

Figure 4. Geometry of the original model of the West Hackberry salt dome in perspective view. (a) Azimuth of 165°; (b) azimuth of 240°; (c) azimuth of 315°; (d) azimuth of 30°; view is from 30° above the horizon; no vertical exaggeration.

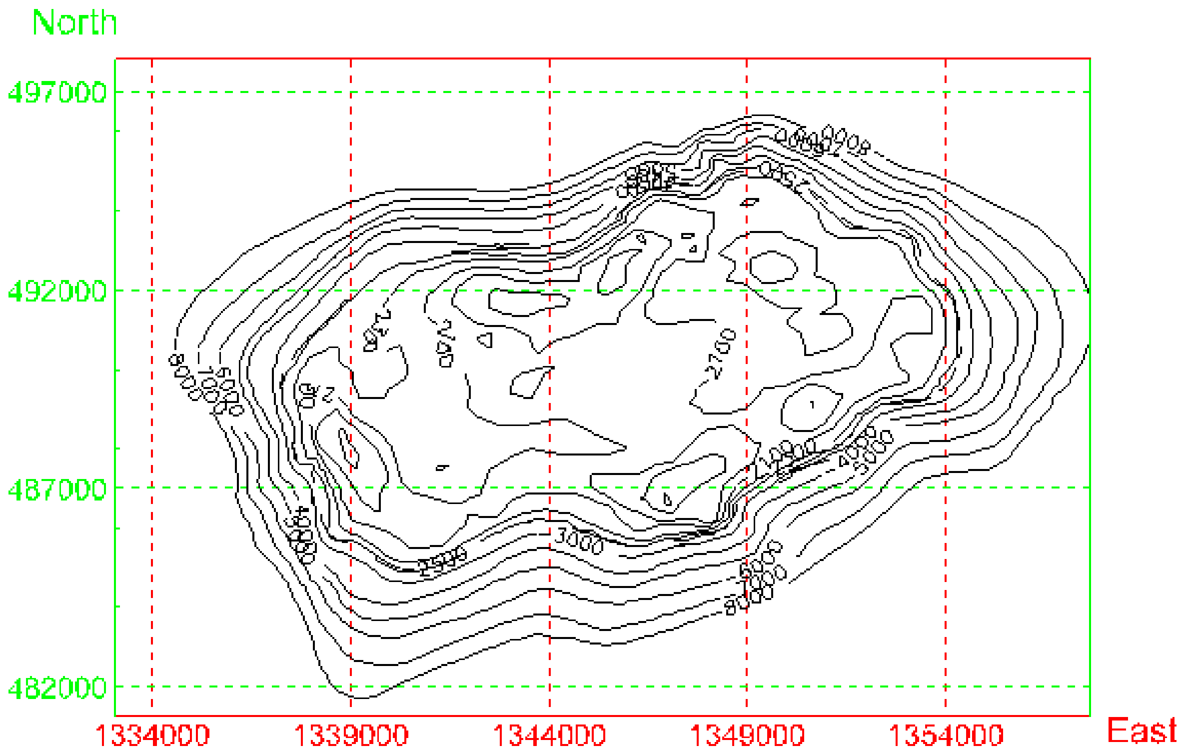

Figure 5. Geometry of the original model of the West Hackberry salt dome shown as a structure contour map. Contours are elevations in feet. View is from directly overhead (elevation = 90°).

A similar presentation of the geometry of the West Hackberry salt dome as modeled by the updated site characterization report is presented in Figures 6 and 7. Figure 6 contains perspective views, also from 30 degrees above the horizontal, whereas Figure 7 shows the top-view structure-contour-duplicating version.

The dome is elliptical in shape and elongated from southwest to the northeast. The contours indicate that the dome narrows towards the northeast to almost a point. The top of the dome is relatively flat and lies at a depth of between 2100 and 2500 feet. The transition from steeply dipping flanks to the relatively flat-lying dome crest occurs between depths of 3000 to 2500 feet. In contrast to the original site-characterization model in Figures 4 and 5, both the flanks and crest of the dome are portrayed in the updated site characterization report as much more smooth and regular in form.

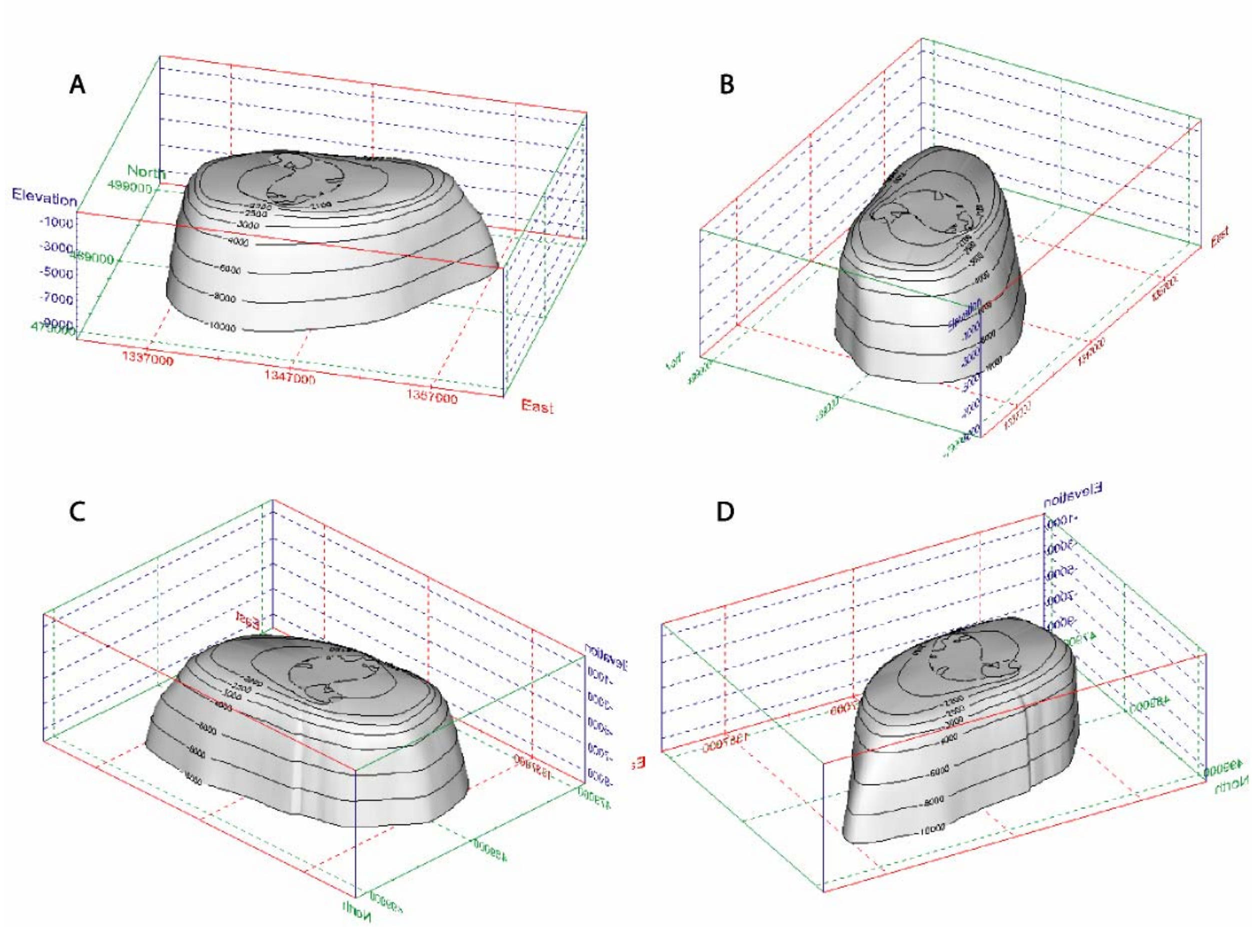

Figure 6. Geometry of the updated West Hackberry salt dome in perspective view. View from azimuths of (a) 165°, (b) 240°, (c) 315°, (d) 30°. Elevation is 30° above the horizontal. Contours are elevations in feet subsea. No vertical exaggeration.

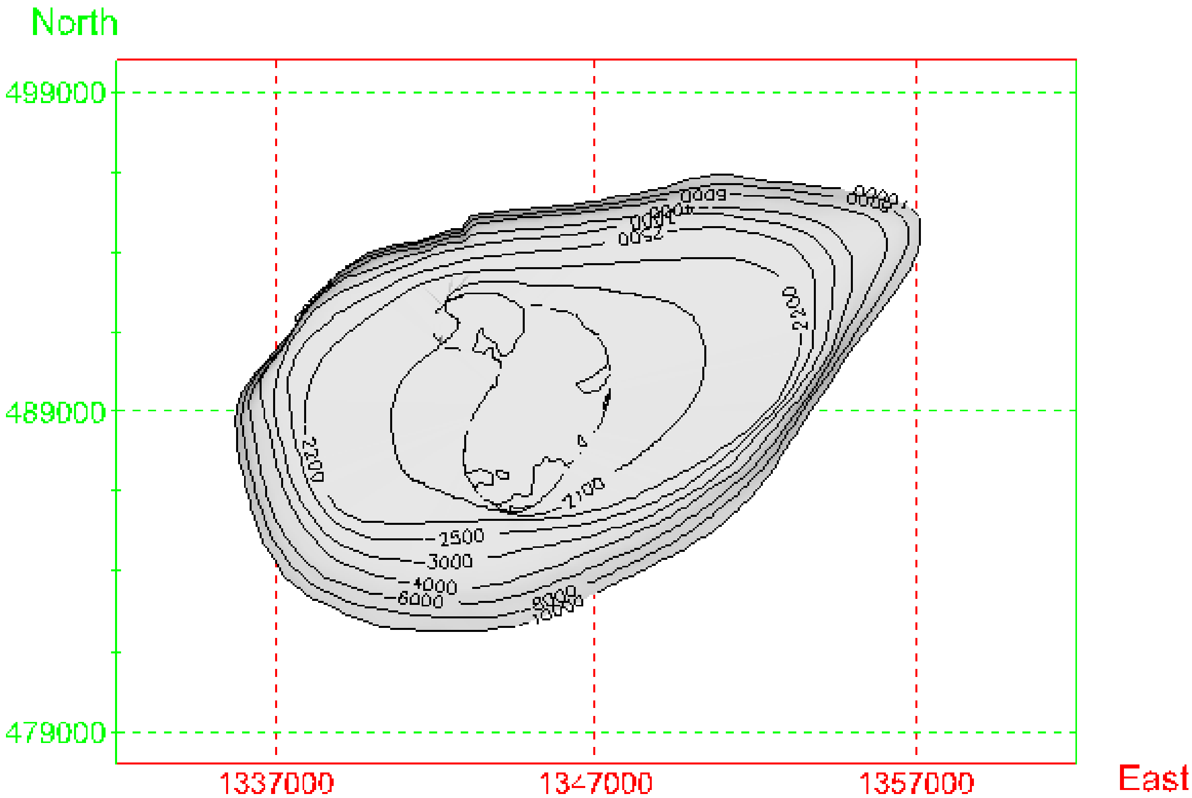

Figure 7. Geometry of the updated West Hackberry salt dome shown as a structure contour map. View is from directly overhead (elevation = 90°).

Sediment Model

The geologic models of the sedimentary layers surrounding the dome are shown in Figures 8, 9 and 10. Figure 8 displays the base of the "B" sand modeled from the structure contour map from the original characterization report (Whiting, 1980). Figures 9 and 10 display the models for the Anahuac and Hackberry shales, respectively, modeled from the structure contour maps in the updated characterization report (Magorian et al., 1991).

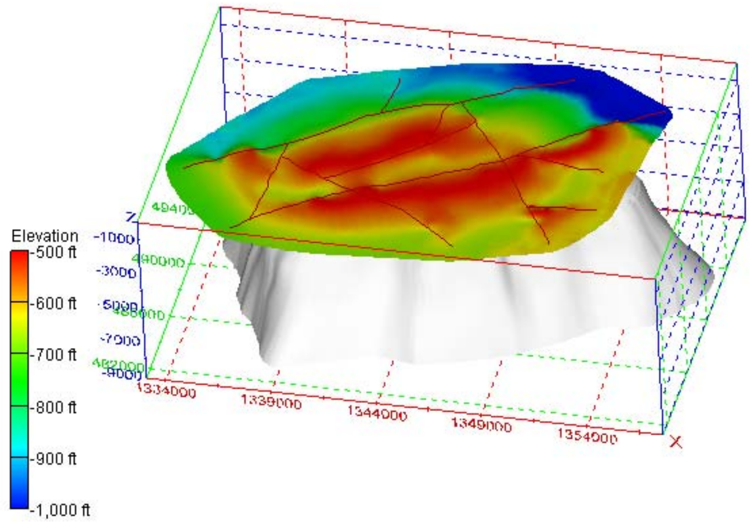

Figure 8. The original West Hackberry salt dome model and the “B” Sand layer colored by elevation subsea and showing fault traces. View is from an azimuth of 165°. Elevation is 40° above the horizontal. No vertical exaggeration.

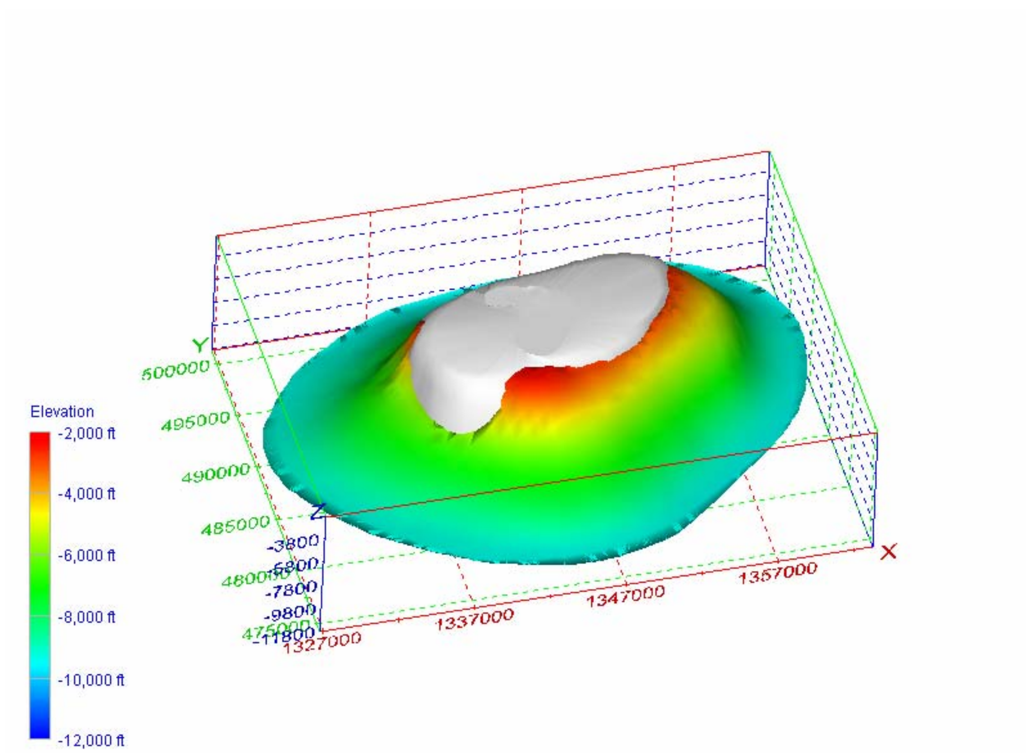

Figure 9. The updated West Hackberry salt dome model shown with the Anahuac shale model. View is from an azimuth 195°. Elevation is 45° above the horizon. No vertical exaggeration.

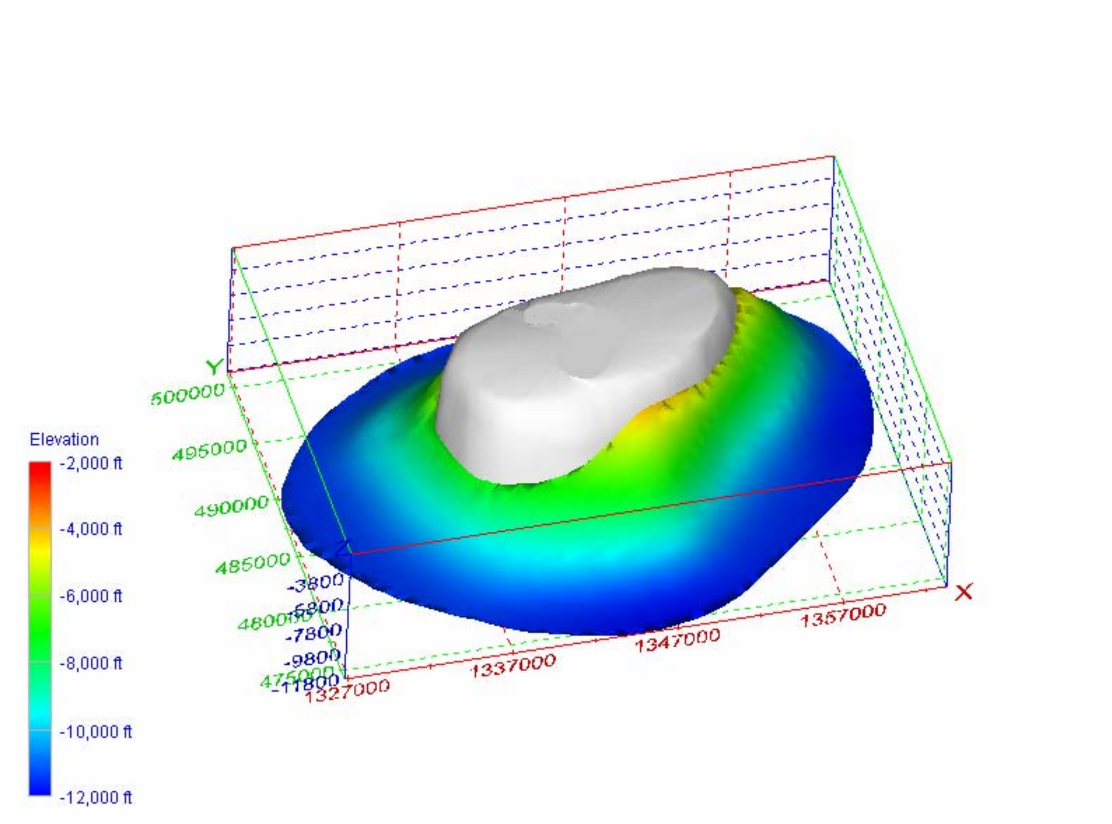

Figure 10. The updated West Hackberry salt dome model shown with the Hackberry shale model. View from an azimuth of 195°. Elevation is 45° above the horizontal. No vertical exaggeration.

CAPROCK MODEL

Caprock is a dissolution product that forms as the dome rises and encounters shallow groundwater. Over time the insolubles (mainly anhydrite) accumulate in a layer at the top of salt. If sufficient hydrocarbons and/or organic matter are present, methane from oxidation of organics and free sulfur from sulfate reducing bacteria can cause the anhydrite to undergo secondary alteration resulting in gypsum or dolomite. The caprock overlying the West Hackberry salt dome has been characterized as containing a lower zone of halite and anhydrite and an upper zone of dolomite and anhydrite, although the data constraining the caprock lithology is sparse (Whiting, 1980).

A structure contour map showing the depth to the top of the caprock, and an isopach map showing the thickness of the caprock were included in the original site characterization report (Whiting, 1980). Updated depth-to-structure maps for the caprock and the salt were included in the updated site characterization report (Magorian et al., 1991). An updated model of caprock thickness was determined by the difference in elevation of the top of caprock and the top of salt. By combining the structure contour and isopach maps in MVS, we produced a 3-D representation of the caprock unit in the updated site characterization report.

A model of the caprock unit at West Hackberry as defined in the original site characterization report is presented in Figure 11 as an isopach map. Perspective views of this model are presented in Figure 12. These images indicate that the caprock is up to 500 ft thick locally, and that the unit is thickest in the central portion of the dome. Recall that the top-of-salt model for the original site characterization report indicated that the central dome crest was slightly below the elevation of the crest-to-flank transition. Thus, the caprock thickness is complimentary to the elevation of the top of salt.

A similar presentation of the model of the caprock defined in the updated site characterization report is given in Figures 13 and 14. These images show that the updated caprock model is thickest in the central portion of the salt dome, but note that the maximum thickness is 100 ft thinner than the original model. Two other features are noteworthy. First, the model shows that the caprock wraps over onto the flanks of the dome on the southeast and northeastern portions. No zero-thickness contour was presented explicitly in the structure contour map of Magorian and others (1991). However, a zero-thickness contour was generated slightly offset from the outermost explicit contours. This approximation of the caprock extent results in a more reasonable amount of caprock extending down the flanks of the dome.

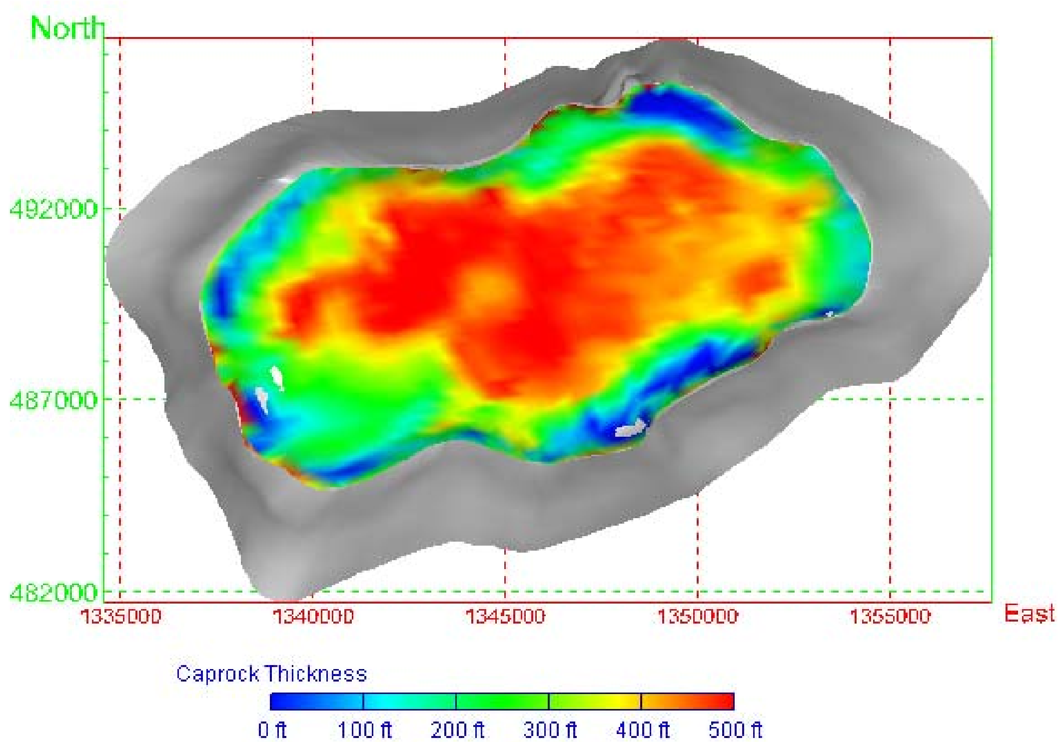

Figure 11. Isopach map showing modeled thickness by color of the caprock according to the original site-characterization report.

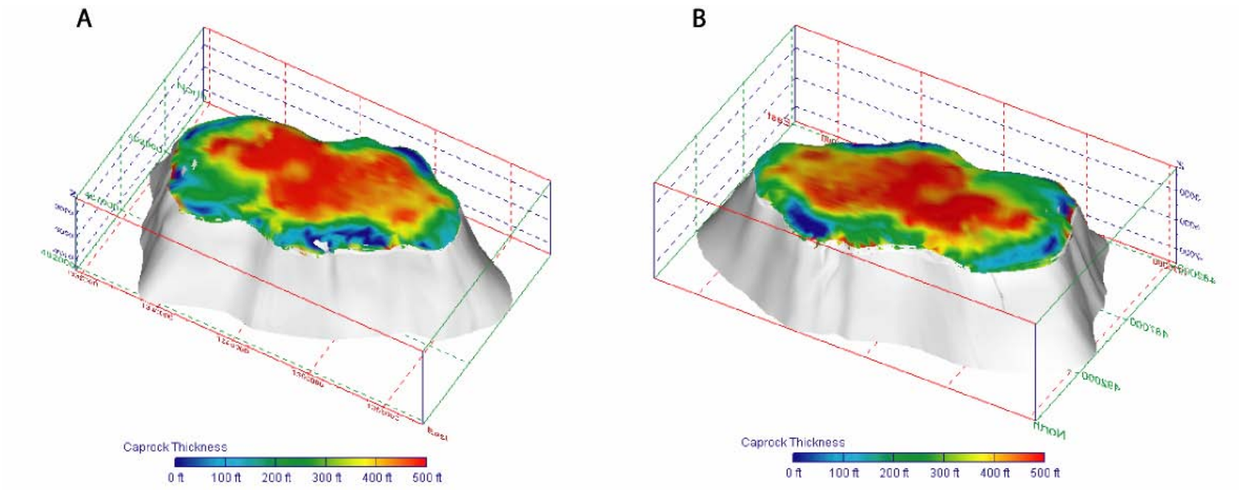

Figure 12. Two perspective views of the original site characterization model of the caprock unit colored by thickness. (a) Azimuth 150°, elevation 50°, (b) azimuth 330°, elevation 40°. No vertical exaggeration.

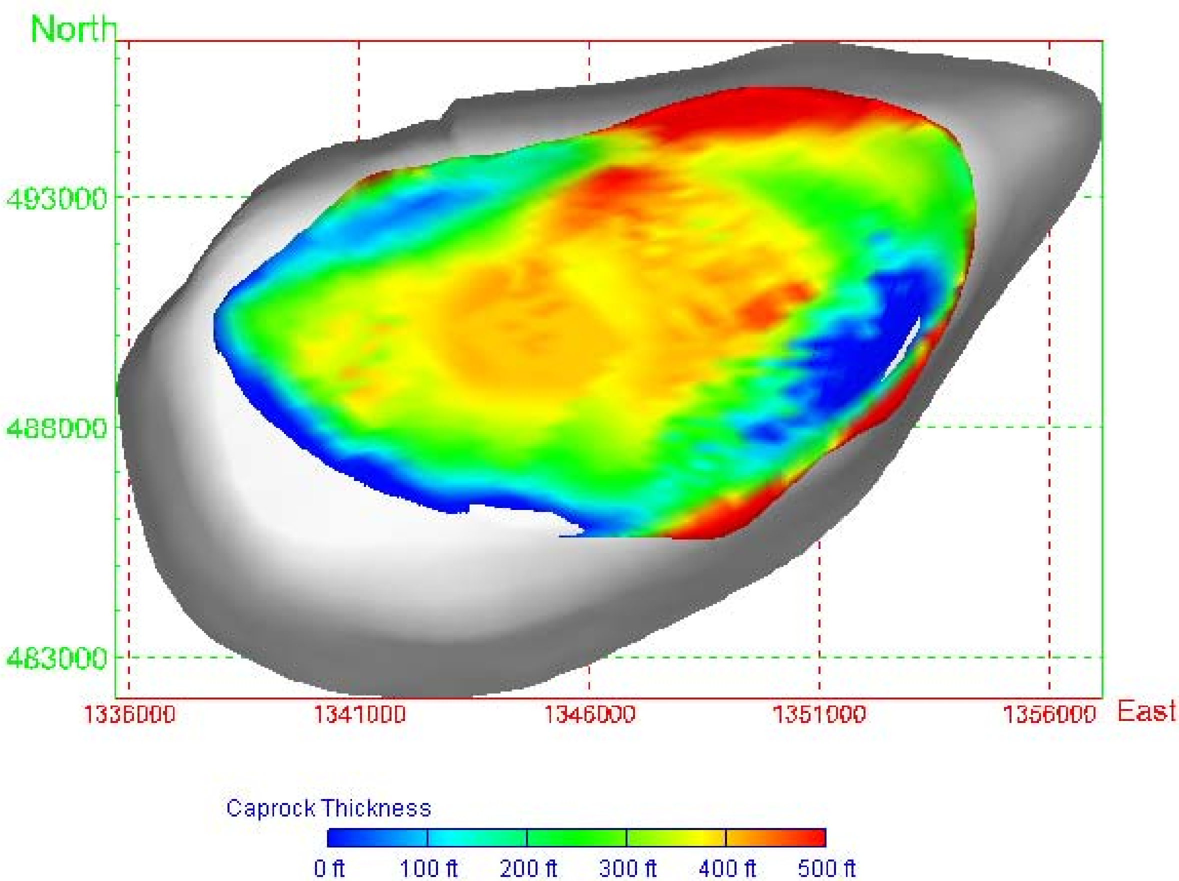

Figure 13. Isopach map showing modeled thickness of the caprock according to the updated site-characterization report. No vertical exaggeration.

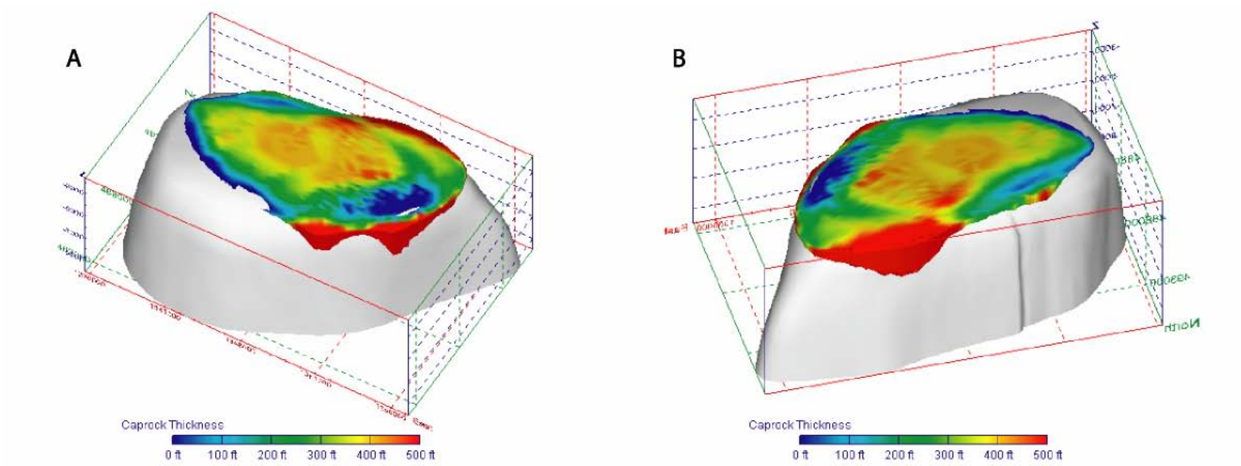

Figure 14. Two perspective views of the updated site characterization model of the caprock unit colored by thickness. Note that the caprock is modeled as wrapping down the flanks of the dome on the southeast and northeastern margins. (a) Azimuth 150°, elevation 50°; (b) azimuth 15°, elevation 40°. No vertical exaggeration.

Fault Models

The geometric models of the two faults in the update site characterization report are displayed in red along with the model of the top of the Hackberry shale in Figures 15 and 16. The faults tend to have relatively steep dips and extend radially away from the edge of the salt dome. In order to allow visualization of a greater vertical extent of the modeled fault planes, only the top of the Hackberry shale is represented in Figures 15 and 16. There is little to no apparent offset represented on the structure contour maps from which the fault traces were digitized. For this reason, no offsets along these faults are seen in the model.

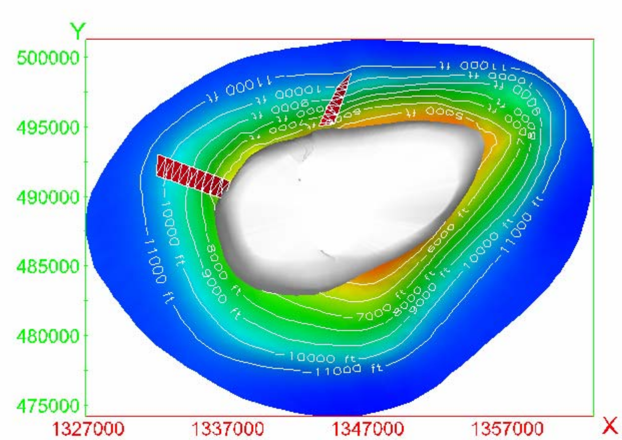

Figure 15. The West Hackberry salt dome model with the Hackberry shale and digitized fault models. Viewed from above.

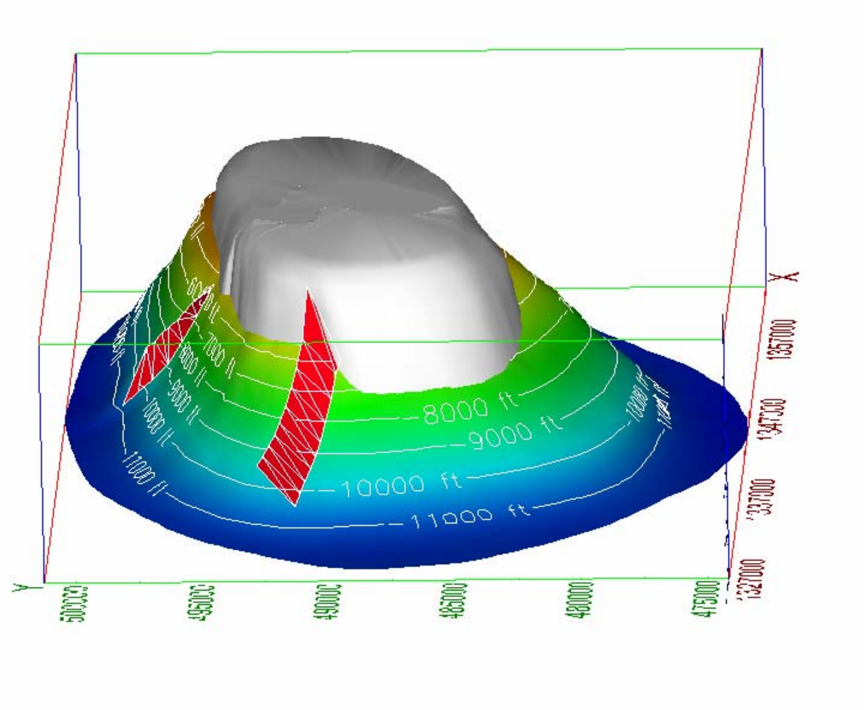

Figure 16. The West Hackberry salt dome model with the Hackberry shale and digitized fault models. Viewed from the west.

Cavern Models

There are 22 oil-storage caverns at the West Hackberry site. The five Phase 1 caverns, WH 6, 7, 8, 9, and 11, which were purchased from the Olin Corp, existed at the time of the 1980 site characterization report. Phase 2 caverns WH-101 – WH-117 were leached after 1980 and are described in the updated site characterization report. Only 12 of the 22 caverns have detailed digital sonar records that have been converted to three dimensional caverns models (Table 2). The remaining caverns are represented in this report as idealized cylinders sized and placed to be nominally representative of the actual geometries and locations of these caverns. Figure 17 shows the position of the cavern field inside the salt dome model. Figure 18 is a close-up view of the cavern field showing individual cavern locations and shapes, as described above.

Table 2. Digital cavern sonar surveys available for visualization.

Cavern ID	Survey Well	Date of Survey	Digital File Name
WH-7	B	7 May 1999	2wh-7b.inp
WH-11	Not specified	28 May 2003	wh-11.inp
WH-101	Not specified	16 Jan 2000	wh-101.inp
WH-103	Not specified	27 Aug 2000	wh-103.inp
WH-104	Not specified	11 Jul 2000	wh-104.inp
WH-105	Not specified	2 Aug 2000	wh-105.inp
WH-106	Not specified	28 Jun 2000	wh-106.inp
WH-107	Not specified	26 Nov 1999	3-wh107.inp
WH-108	Not specified	22 Apr 2003	wh-108.inp
WH-109	Not specified	14 Mar 1997	wh-109.inp
WH-113	Not specified	4 Nov 2000	wh-113.inp
WH-116	Not specified	22 Apr 2000	wh-116.inp

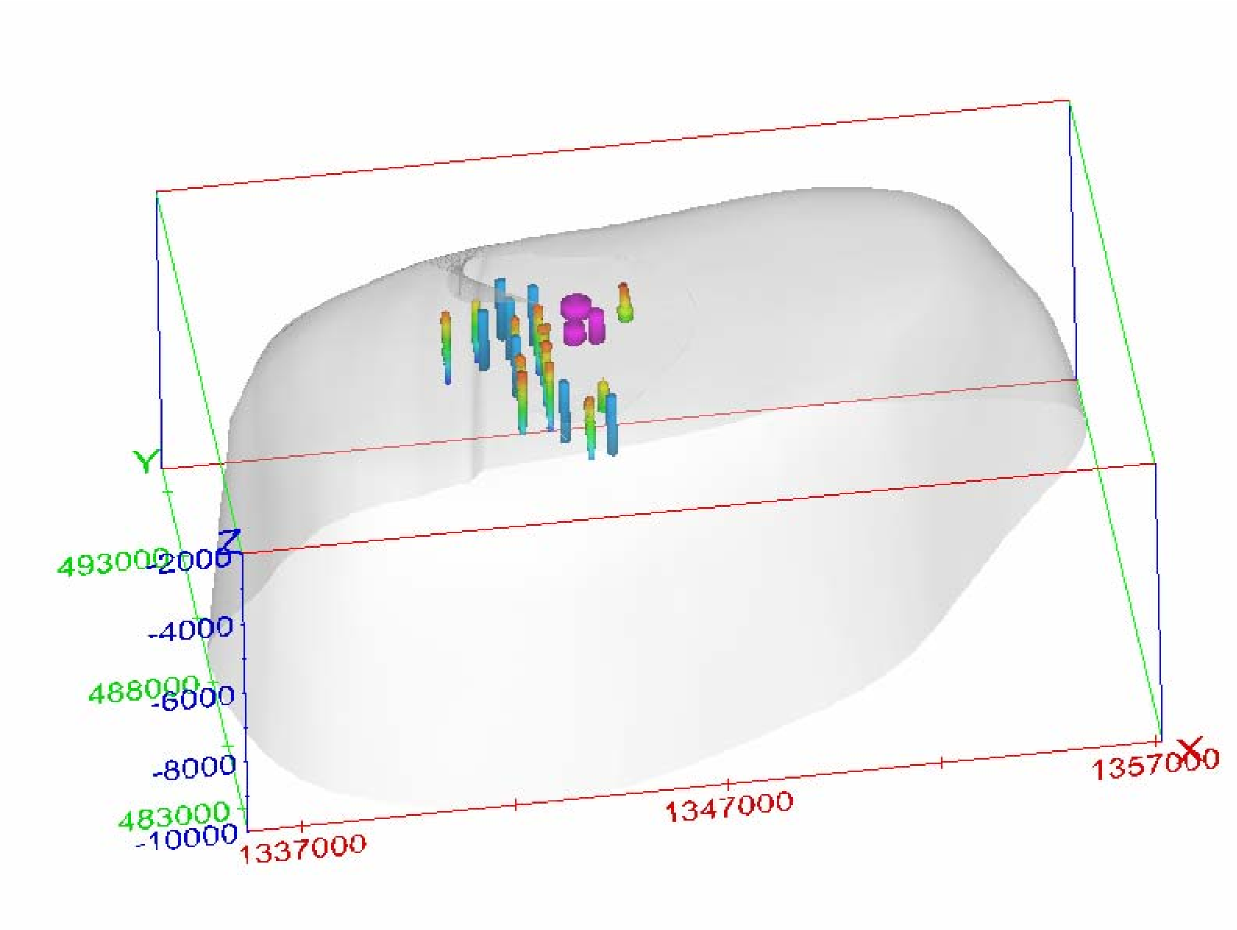

Figure 17. Visualization of sonar logs from 12 of the 22 caverns at West Hackberry shown with a transparent view of the dome model. Twelve of the cavern models were generated from actual sonar logs are colored by elevation. Phase 1 caverns without sonar logs are represented as pink cylinders. Phase 2 caverns without sonar logs are represented as blue cylinders

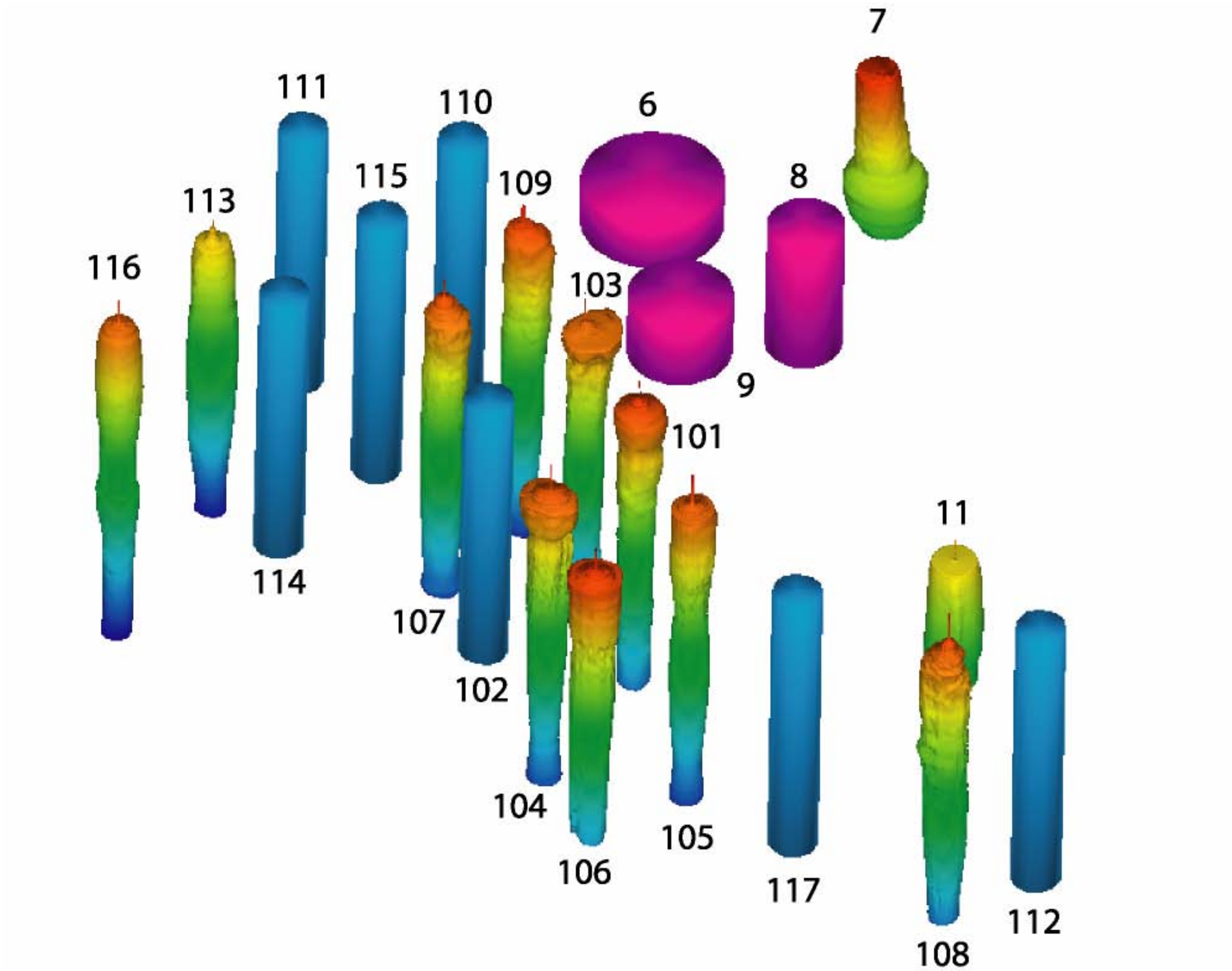

Figure 18. Visualization of the 22 oil-storage caverns at West Hackberry SPR site viewed from the south. Twelve of the cavern models (colored by elevation) were generated from actual sonar logs. Phase 1 caverns without sonar logs are represented as pink cylinders. Phase 2 caverns without sonar logs are represented as blue cylinders. Non-sonar cavern shapes are not to scale and are only meant to be nominally representative of the actual shapes.

DISCUSSION

Salt Dome Model

The two models of the West Hackberry salt dome are compared in Figure 19 by showing the original model in gray and the updated model in red superimposed on the same figure. This method of presentation helps to highlight the differences in the models.

The original dome model is elongate and not as smooth or cylindrical in shape, and the northeast side of the domes does not thin to form a point as the updated model.

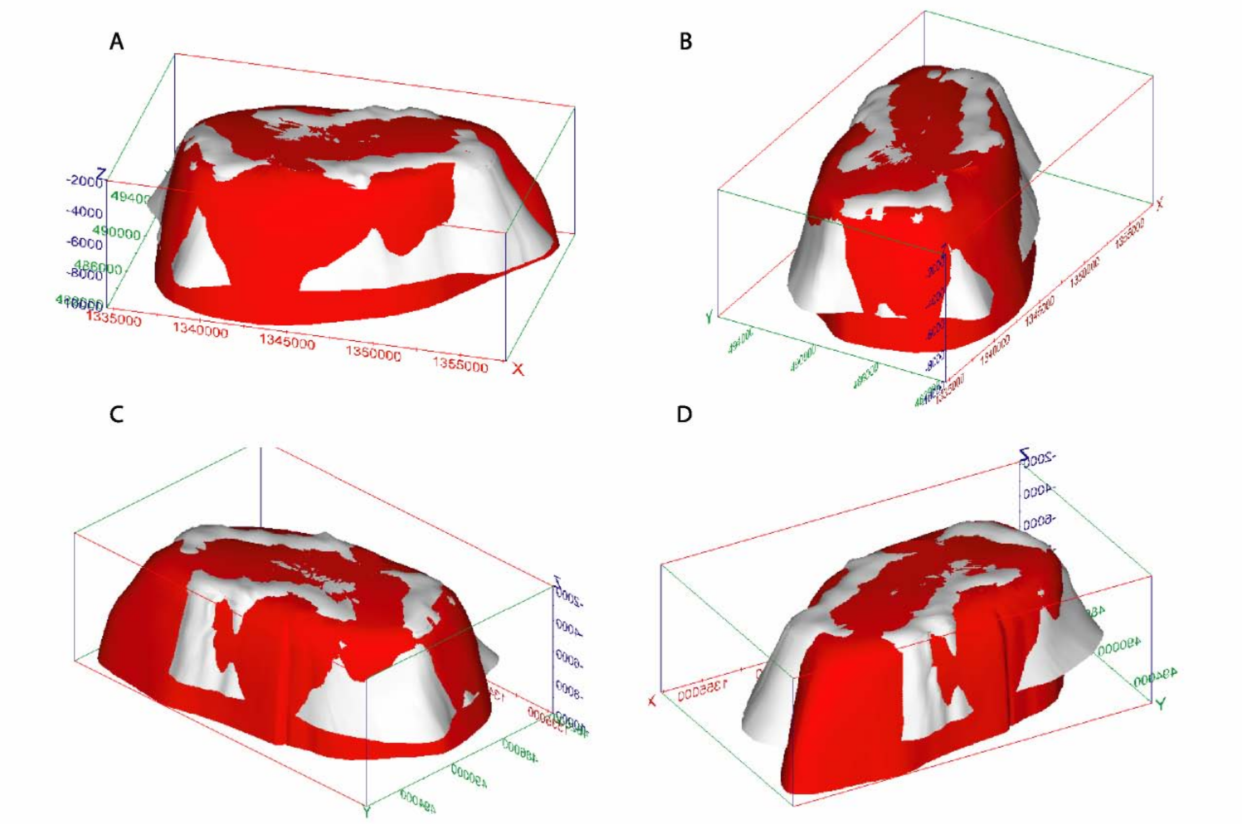

Figure 19. Comparison of the original (gray) and updated (red) West Hackberry salt dome models in perspective view. View from azimuths of (a) 165°, (b) 240°, (c) 315°, (d) 30°. Elevation is 30° above the horizontal. No vertical exaggeration.

Sediment Model

The models of the sedimentary layers surrounding the salt dome presented in this conversion report are very limited in the sense that they only represent the top surface of two units and the bottom surface of one unit out of a stratigraphy that contains many more geological units (see Table 1). If well locations could be determined for the wells listed in the Appendix D of the update site characterization report, it would be possible to generate a more complete model of the surrounding geology based on the available data.

The sediment models presented do exhibit the standard features that are expected for sedimentary layers pierced by diapiric salt domes, including upturned sediment layers near the dome and radial faulting as the result of upward movement of the salt over time. The base of the “B” Sand, which lies above the caprock exhibits significant faulting as a result of differential movement from the periodic collapse of the caprock as the underlying salt dome is dissolved by groundwater and the general movement of the dome upward.

Another limitation of the current sediment model is that it is limited to defining the tops or bottoms of the various sedimentary units. There is no information in the site characterization report that defines the presumably varying layer thickness of these units. If the thickness of the sedimentary units needs to be defined in the future, the original well logs from those wells will have to be located and reinterpreted.

Fault Models

The fault models presented in this report are idealized. The models are based on inferred fault traces digitized from two structure contour maps. The process of estimating the location of a subsurface fault plane is quite subjective when the data density is low, as is the case at the West Hackberry site. Because the details on how these traces were selected are not well documented in the site characterization report it is difficult to evaluate the validity of the interpretations. A better strategy would be to try to obtain adequate seismic data that could help to image the fault geometry. At present, such data are not available.

Cavern Models

The cavern models based on the sonar caliper logs are the best-constrained models presented in this report. Each nodal point on a cavern mesh is constrained by individual sonar measurements. However, digital versions of sonar logs are not available for every cavern at West Hackberry and therefore the exact geometry of the remaining caverns is not known with certainty at the present time. Numerous sonar logs were run in each of the Phase 2 cavers at West Hackberry at different times during cavern development, but many of these logs are only available in paper format. In order to convert these to 3-D digital models it is necessary to convert the paper data tables into a digital file, either by manual data entry or by scanning the paper record and employing optical character recognition (OCR) software. In either case, this process is slow and has not been completed for all caverns.

CONCLUSIONS

We have presented a set of 3-D geologic models of various features of the West Hackberry SPR site. The models are constrained by structure contour maps presented in the original and updated site characterization reports. The features of the models include the geometry of the salt dome, selected sedimentary surface layers, faults, and oil storage caverns. Several features are modeled differently in each of the site characterization reports. The variability in these models provides some an indication of spatial uncertainty in the geology.

Three dimensional modeling is a significant improvement on the original 2-D method of geologic representation because it is geometrically and geologically consistent. The models presented here provide a baseline for future work at the West Hackberry site and can easily incorporate new data as it becomes available. As a next step, it would be valuable to reconcile borehole names and locations in order to include the geologic data listed in the appendix of the update report into a more consistent and more complete geologic model. Future needs of the project, such as a possible expansion of the reserve may require an improved understanding of the geology surrounding the West Hackberry and other SPR sites. The present set of models provides the framework for such model improvements.

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Magorian, T.R., Neal, J.T., Perkins, S., Xiao, Q.J., and Byrne, K.O., 1991. Strategic Petroleum Reserve (SPR) Additional Geological Site Characterization Studies, West hackberry Salt Dome, Louisiana. Sandia Report SAND90-0224, Sandia National Laboratories, Albuquerque, NM.

Rautman, C.A., and Stein, J.S. 2003. *Three-Dimensional Representations of Salt-Dome Margins at Four Active Strategic Petroleum Reserve Sites*. SAND2003-3300. Albuquerque, NM: Sandia National Laboratories. 70 p.

Whiting, G.H., ed., 1980. Strategic Petroleum Reserve (SPR) Geological Site Characterization Report, West Hackberry Salt Dome. Sandia Report SAND80-7131, Sandia National Laboratories, Albuquerque, NM.

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APPENDIX A: INSTALLATION AND USE OF 4DIM FILES

Introduction

This appendix describes a powerful and relatively novel means for examining a three- dimensional geologic model. The geological modeling software environment collectively known as MVS (Mining Visualization System) developed by C Tech Development Corporation (www.ctech.com) includes a derivative model “type” known as 4DIM files (for 4- Dimensional Interactive Model). 4DIM models are fully three-dimensional representations of selected model components developed through the use of C Tech’s modeling software.

The unique aspect of 4DIM models is that they are user manipulable. In contrast to a static still image or screen capture, the user may rotate, pan, and zoom in or out on any part of the model that is desired. The ability to rotate and change the viewing perspective of a three-dimensional model may be critical to understanding and conceptualizing the detailed spatial relationships, in that objects closer to the viewer behave in subtle but importantly different ways than objects located farther away. Such interaction with a model is simply not possible in any static view.

C Tech Development Corporation makes an “unlicensed” 4DIM viewer freely available over the internet. A “licensed” version is also available for purchase. Unlicensed in this context means that the player will not play all 4DIM files. A specially encoded 4DIM file is required. Only 4DIM models that have been created using the higher-end versions of C Tech software are capable of writing such model files. 4DIM models generated by the lower-cost and more simplistic versions of C Tech’s software do not generate these encoded files, and thus a licensed version of the 4DIM player is required to view these files. This situation is clearly a marketing strategy aimed an encouraging purchase and use of the higher- end products.

Sandia National Laboratories owns MVS, the top-end modeling software produced by C Tech Development Corporation. Accordingly, all 4DIM files generated using MVS are encoded with the necessary key for use with the unlicensed version of the player.

Software Installation Instructions

The 4DIM player software currently (2003) runs on personal computers under the Microsoft Windows™ operating system. The unlicensed version of the player may be downloaded over the internet from http:\\www.ctech.com. As the website changes episodically, some internal navigation of the site may be required to locate the downloadable version. A functioning version of the unlicensed 4DIM player is included on the CD-R at the back of this report. Administrator privileges are required to install the 4DIM player. However, these privileges are not required for routine running of the software.

To install the 4DIM player, locate the file `4DIM_setup.exe`, within the `install` subdirectory (folder) of the CD-R. Note that the .exe extension will not necessarily be visible if the Windows file manager option to “`Hide file extensions for known file types`” option is checked. Double-click or otherwise open this file. The preferred installation location on a standard PC is in a c:\4DIM directory (at the root level of the boot or system disk). This is the default location, and it may be changed as desired so long as the caveat regarding installation to a directory whose name contains a space is observed. All defaults may simply be accepted during the installation process.

Software Operating Instructions

Once properly installed, the file extension ".4d" is associated by Windows with 4DIM model files and with the 4DIM player. Therefore, a 4DIM model may be viewed simply by navigating to the storage location of any .4d file and double-clicking on the relevant icon. The 4DIM player may also be started via the Windows Start - Programs menu command structure or by use of a desktop shortcut. In either of these latter instances, it will be necessary to open a particular 4DIM model file using the player's File - Open menu command. The remaining menu buttons operate an a manner consistent with standard Windows programming.

Once a .4d file is opened in the viewer, the visible model may be manipulated as follows:

1. To rotate the model, left-click and drag somewhere on the visible model.
2. To pan (shift) the model on the screen, right-click and drag somewhere on the model.
3. To zoom in, left-click while holding down the Shift key and move the mouse pointer upward on the screen. To zoom out, left-click while holding down the Shift key and move the mouse pointer downward on the screen. Zooming in either direction is toward the center of the screen, so it may be necessary to pan the model (see above) to maintain the desired location on the screen.
4. To specify the view from a particular direction, open the Az-El (azimuth & elevation) menu button at the top of the 4DIM player screen. This operation will bring up a separate window that will allow specification of the azimuth from which to view the model, the elevation above (+) or below (–) the horizon from which to view the model, and the scale factor which controls the magnification of the image. Either the radio buttons or the slider bar or the indicated type-in boxes may be used to specify the view.
5. If the view becomes hopelessly confused or the model disappears completely from view, there are two ways to recenter the default view: (a) Use the "RNC" menu button at the top of the 4DIM player screen or click on the multicolored button on the Az-El window.

More than one interactive "model" may be contained in a 4DIM file. If this is the case, the slider bar at the bottom of the main player window will indicate "Current frame [xx of nn]," where nn is the total number of individual model representations within the file. To step through the sequence of a multi-frame 4DIM file, simply click on the arrows at either end of the slider bar or left-click and drag on the slider itself.

Depending upon how a 4DIM file containing multiple model representations was constructed, the successive frames may constitute an animated sequence. To view such sequence, use one or more of the eight arrow buttons at the bottom left of the main player window. It will most likely help to increase the "Delay (seconds)" setting on the bottom right of the main window from its default value of 0.00. This sets the time between successive images, and the value may be adjusted as desired to achieve an aesthetically pleasing progression of frames.

An important setting for 4DIM files generated by Sandia National Laboratories is the screen background color. The default value is black. However, many sequences contained on the CD-R with this report are predicated on a white background. Certain text and other objects may not be visible unless this setting is changed. To do so, issue the menu command "Settings **|** View **|** Background **|** Set to white."

List of 4DIM Model Files for West Hackberry SPR Site

A set of ten 4DIM files are included on the CD-R as part of this report. The files are all 3-D versions of the still figures in the report. Files are named with reference to the figure numbers. See figure captions and descriptions in the report for discussion of the features included in the models. Below is a list of the ten 4DIM files included:

	FILENAME	FIGURES
1.	File WH_FIG4-5.4d	Figures 4-5
2.	File WH_FIG6-7.4d	Figures 6-7
3.	File WH_FIG8.4d	Figure 8
4.	File WH_FIG9-10.4d	Figures 9-10
5.	File WH_FIG11-12.4d	Figures 11-12
6.	File WH_FIG13-14.4d	Figures 13-14
7.	File WH_FIG15-16.4d	Figures 15-16
8.	File WH_FIG17.4d	Figure 17
9.	File WH_FIG18.4d	Figure 18
10.	File WH_FIG19.4d	Figure 19

DISTRIBUTION:

U.S. Department of Energy (via CD-R only)
Strategic Petroleum Reserve Project Management Office
900 Commerce Road East
New Orleans, LA 70123

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Strategic Petroleum Reserve Program Office
1000 Independence Avenue, SW
Washington, D.C. 20585
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MS 0706 C.A. Rautman, 6113 (5)
MS 0706 A.R. Sattler, 6113
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